# 2. MODELING FOR PESTICIDE PRODUCTIVITY MEASUREMENT*

Darwin C. Hall and L. Joe Moffitt

## ABSTRACT

*This paper revisits claims about implications of production function specification for pesticide productivity measurement and presents two extensions of the popular damage control specification, along with an empirical application. One extension eliminates bias caused by relying solely on economic data and shows how to include variables that represent the pest population when they are necessary to avoid bias. The second extension allows for the possibility of phytotoxicity. These extensions generalize the damage control specification by eliminating bias and allowing for a range over which the first and third stages of production may occur. The main contributions of the analysis are to clarify existing misconceptions about pesticide productivity modeling and to provide extensions to the damage control specification that permit greater realism for empirical analysis.*

* An earlier version of this paper was presented at a pesticide economics conference held at the University of Massachusetts in honor of the memory of Carolyn R. Harper.

**Economics of Pesticides, Sustainable Food Production and Organic Food Markets**
**Volume 4, pages 21–35.**

**ISBN: 0-7623-0850-8**

## 1. INTRODUCTION

Virtually all types of management strategies related to pest control in agriculture require knowledge of the impact of pest density on crop production and the relationship between density and pest control inputs (e.g. Marsh, Huffaker & Long, 2000; Saphores, 2000; Sunding & Zivin, 2000). The estimated form of such relationships can be critical for farm-level decision making and for public policy analyses as well. Not surprisingly, the econometric specification of such models has been the subject of a number of studies (Lichtenberg & Zilberman, 1986; Carrasco-Tauber & Moffitt, 1992; Du et al., 2000).

This paper begins by clarifying misconceptions that have resulted from conceptual problems underlying the damage control model formulated by Lichtenberg and Zilberman (1986). Following this, we pursue important extensions to the damage control model for empirical work. The model can be extended in one way by explicitly recognizing the process by which inputs control for damage. The extension in this paper reveals a second source of bias when estimating the pesticide production/cost relationship solely with measures of outputs, inputs, costs and/or prices. If the inputs to control damage are not applied prophylactically, then the estimators proposed by Lichtenberg and Zilberman are biased; to avoid bias it is necessary to specify the damage and control relationship and measure the state variables (pest population) that cause the damage. Economic variables alone are insufficient; to estimate pesticide productivity it is necessary to measure and model variables from Mother Nature, as well as economic variables.

A second extension of the damage control specification is essential to estimate the productivity of herbicides. If the herbicides have phytotoxic effects, then the estimators proposed by Lichtenberg and Zilberman are biased; this second extension avoids bias caused by phytotoxicity. More generally, the two extensions in this chapter account for circumstances where the input that controls damage may also cause damage.

## 2. DAMAGE CONTROL MODEL AND PRODUCTIVITY

In their frequently cited study, Lichtenberg and Zilberman (1986) argued that pesticide inputs should be entered into econometric production function models in a different manner than other inputs. Their suggestion was to encapsulate the pesticide variable in an abatement function; i.e. a function that maps the pesticide variable onto the unit interval, and to enter the abatement function rather than the pesticide variable into the production function. We refer to their model as the damage control model. Some earlier studies (e.g. Moffitt & Farnsworth, 1981) used the same kind of functional specification; however, Lichtenberg and Zilberman (1986) were the first to attempt to provide an econometric rationale for using such an abatement relationship. A number of pesticide productivity studies done subsequent to Lichtenberg and Zilberman (1986) have also used their notion of a damage control model.

As measured by its apparent impact on subsequent literature (e.g. Fox & Weersink, 1995), perhaps the main substantive conclusion of Lichtenberg and Zilberman (1986) is that the use of a standard Cobb-Douglas type production function to estimate pesticide productivity leads to overestimation of the marginal product of pesticide. More specifically, they conclude that if the damage control model is the true model, then least squares estimates of the marginal product of pesticide derived from a Cobb-Douglas production function will overestimate the true marginal product of pesticide for all values of pesticide above the geometric mean of pesticide use contained in the statistical database. Figure 1 depicts the main result diagrammatically. While several criticisms have been leveled at various features of the Lichtenberg and Zilberman (1986) analysis (e.g. Pandey, 1989; Blackwell & Pagoulatos, 1992), the main conclusion depicted in Fig. 1 has apparently never been disputed.

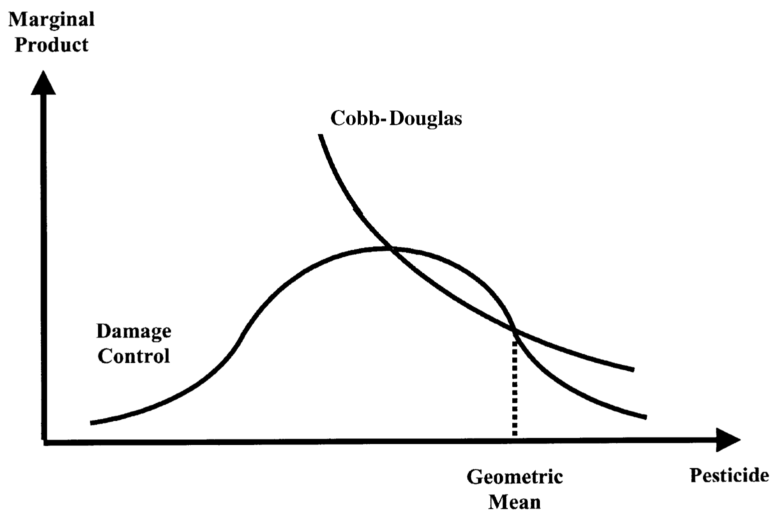


*Fig. 1.* Alleged Relationship Between Marginal Products Estimated using Cobb-Douglas and Damage Control Models.

As shown below, because of a conceptual problem in the Lichtenberg and Zilberman (1986) derivations, their analysis does not support the main conclusion of their study (Fig. 1) that is, in fact, incorrect. This observation is perhaps not surprising when one abstracts from the context in which their study was conducted and views their model simply as a regression relationship. So, before getting into details, note that in the abstract their study purports to show that the slope of a nonlinear functional form will be overestimated if least squares regression and a log-linear form are applied erroneously to the data generated by the true nonlinear form. When viewed from this perspective, it is apparent that this is a very tall order. While the particular nonlinear functional forms for which the Lichtengerg and Zilberman (1986) result holds are unclear, it is clear from the following analysis that the result does not hold when the nonlinear functional form is the damage control model.

The main criticism of the Lichtenberg and Zilberman (1986) conclusions about relative magnitudes of marginal products estimated using the Cobb-Douglas and damage control models is based on the fact that they draw their conclusions from comparisons with numbers that are not estimated marginal products. The main flaw in the Lichtenberg and Zilberman (1986) reasoning occurs in their Eqs (A7) and (A8) (Lichtenberg & Zilberman, 1986, p. 273). Some discussion of marginal product and its evaluation is useful to see the conceptual problem embodied in their reasoning. The marginal product (MP) of an input can, of course, be evaluated at any level of input use. Lichtenberg and Zilberman (1986) defined Q as output, Z as a vector of ordinary inputs, and X as a damage control input. Using the Lichtenberg and Zilberman (1986) notation, if the production model is $Q = F(Z, X) = \alpha Z^{\beta} X^{\gamma}$, then $MP_X = \partial Q/\partial X = \gamma\alpha Z^{\beta} X^{\gamma-1} = \gamma F(Z,X)/X$ which obviously depends on the values of Z and X. In particular, $MP_X$ at the arithmetic means $\bar{Z}$ and $\bar{X}$ of the input variables, say $MP_X(\bar{Z}, \bar{X})$, is $\gamma F(\bar{Z}, \bar{X})/\bar{X}$ while $MP_x$ at the geometric means, Z* and X*, say $MP_X(Z^*, X^*)$, is $\gamma F(Z^*, X^*)/X^*$. Note that the arithmetic mean of a variable X given n observations is defined as $(1/n)\Sigma_{i=1}^{n} X_i$ while the geometric mean is defined as $\Pi_{i=1}^{n} X_i^{1/n}$.

Marginal products for inputs in production models estimated by ordinary least squares (OLS) in double-log form are commonly reported at the geometric means. This point is selected for evaluation because, due to a property of OLS, the marginal product calculation is simplified at the geometric means. To see this, note that in the Lichtenberg and Zilberman (1986) notation, the double-log form of $Q = \alpha Z^{\beta} X^{\gamma}$ is $\ln Q = a + \beta \ln Z + \gamma \ln X$, where $a = \ln \alpha$. Given n observations on Q, Z, and X, OLS parameter estimates are known to provide an exact fit at the arithmetic means of the data variables (here data variables are logarithms – ln Q, ln Z, and ln X); that is,

$(1/n)\Sigma_{i=1}^{n} \ln Q_i = \hat{\alpha}_{OLS} + \hat{\beta}_{OLS}(1/n)\Sigma_{i=1}^{n} \ln Z_i + \hat{\gamma}_{OLS}(1/n)\Sigma_{i=1}^{n} \ln X_i$. Exponentiation of both sides gives $Q^* = \hat{\alpha}_{OLS}Z^*\hat{\beta}_{OLS}X^*\hat{\gamma}_{OLS} = F(Z^*, X^*)$; that is, the geometric means of output and the inputs are a point on the fitted production function. Since $Q^* = F(Z^*, X^*)$, marginal product at the geometric means, $\hat{\gamma}F(Z^*, X^*)/X^*$, can be evaluated as $\hat{\gamma}Q^*/X^*$. This simplification perhaps explains why the geometric means have traditionally been used for reporting estimated marginal products for Cobb-Douglas type production functions fitted in double-log form by OLS (see e.g. Headley, 1968).

The very convenient calculation of $MP_X$ at the geometric means is facilitated by a substitution based on the fact that $Q^* = F(Z^*, X^*)$. However, this type of substitution is not possible at any other level of input use for the OLS estimated double-log case. In particular, use of the arithmetic means of output and the inputs to form $\hat{\gamma}\bar{Q}/\bar{X}$ as $MP_X$ is inappropriate because $\bar{Q} \neq F(\bar{Z}, \bar{X})$ in finite samples or asymptotically. It is important to note that $\hat{\gamma}\bar{Q}/\bar{X}$ and related expressions contained in Eqs (A7) and (A8) of Lichtenberg and Zilberman (1986) are not marginal products by definition. Hence, their relative magnitude does not predict the relative magnitude of marginal products that will be forthcoming from use of Cobb-Douglas type and damage control specifications of production. It is use of this erroneous substitution by Lichtenberg and Zilberman (1986) in their Eqs (A7) and (A8) that leads to the erroneous conclusions drawn concerning the relative magnitudes of marginal products estimated using Cobb-Douglas type and damage control production models.

Empirical confirmation of the above is provided by results contained in Carrasco-Tauber and Moffitt (1992, p. 160). Table 1 shows their estimated marginal products for various farm inputs using both a Cobb-Douglas type production model and the Weibull abatement function version of the damage

***Table 1.*** Estimated Marginal Products Evaluated at the Geometric Mean Using Cobb-Douglas Type and Damage Control Models, U.S. Agriculture 1987

| Input | Cobb-Douglas Type | Damage Control Model |
|---|---|---|
| Labor | 44.54 | 46.53 |
| Land and Buildings | 0.04 | 0.04 |
| Machinery | 1.25 | 1.27 |
| Other | 1.29 | 1.29 |
| Fertilizer | 2.72 | 1.84 |
| Pesticide | 5.94 | 6.88 |

*Source:* Carrasco-Tauber and Moffitt (1992).

control model. Marginal products in the table are evaluated at the geometric means of the sample data variables. According to the Lichtenberg and Zilberman (1986) finding (Fig. 1), the marginal products using the different models should be the same at the geometric means. However, the Cobb-Douglas type model actually provides a lower estimated marginal product than that estimated with the damage control model (Table 1).

Even though sweeping econometric generalizations for the superiority of the damage control model relative to alternatives are not possible, use of the abatement function to encapsulate the pesticide variable(s) makes intuitive sense. Even greater intuitive appeal may be afforded specifications that extend the damage control model to account for the pest population and the notion of phytotoxicity. The next section focuses on extending the damage control model in both of these directions.

## 3. EXTENSIONS OF THE DAMAGE CONTROL SPECIFICATION

The original damage control specification is given as:

$$Q = F_1(Z) + F_2(Z)G(X) + \varepsilon \tag{1}$$

where

$$F_1(Z) = \text{minimum output} \tag{2}$$

$$F_1(Z) + F_2(Z) = \text{potential output} \tag{3}$$

and

$$0 \le G(X) \le 1 \tag{4}$$

Output is Q. The vector Z represents usual inputs, and the vector X represents inputs to control damage. When $G(X) = 1$, no damage occurs, and when $G(X) = 0$, the maximum damage occurs. G(X) gives the proportion of damage avoided by the control variable X. This model is illustrated in Fig. 2. Note that the initial pest infestation is not specified in the model.

In the case of pesticides, the damage control specification would account for varying infestation levels of the pest population, B, by including it as an argument in $F_1$ and G:

$$Q = F_1(Z, B) + F_2(Z)G(X, B) + \varepsilon \tag{5}$$

To explain Eq. (5), consider the simplest model with linear damage and a bug infestation equal to $B_1$, so $Q = Q_0 - \delta B_1$. Obviously, if enough pesticide is applied to kill the entire pest population, then output would equal $Q_0$, but

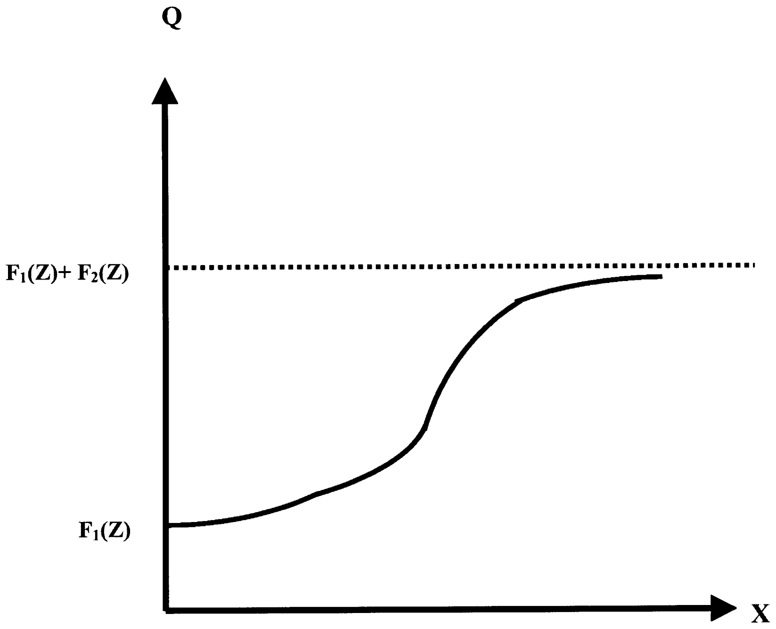


*Fig. 2.* Damage Control Specification.

without application of pesticide, output equals $Q_0 - \delta B_1$, shown in Fig. 3. Therefore, the output with zero pesticide application, $F_1$ in the damage control model, is a function of the initial infestation B. With a higher level of infestation, $B_2$, if no pesticide is applied then output is lower, equal to $Q_0 - \delta B_2$ as shown in Fig. 3. The proportion of damage avoided will in general depend not only on the amount of pesticide but also on the initial infestation. So, for example, if $X = X^*$ in Fig. 3, the proportion of damage depends on whether the initial bug population equals $B_1$ or $B_2$:

$$Q_1^* = F_1(Z, B_1) + F_2(Z)G(X^*, B_1) \quad (5a)$$

$$Q_2^* = F_1(Z, B_2) + F_2(Z)G(X^*, B_2) \quad (5b)$$

and the proportions of damage for the two initial infestations, $B_1$ and $B_2$, are $(Q_0 - Q_1^*)/Q_0$ and $(Q_0 - Q_2^*)/Q_0$.

When the initial bug infestation population is omitted in the econometric estimation, then it is included in the error term. For any IPM program (Hall & Duncan, 1984), where the quantity and timing of pesticide application awaits an infestation greater than the economic threshold (Headley, 1971; Hall &

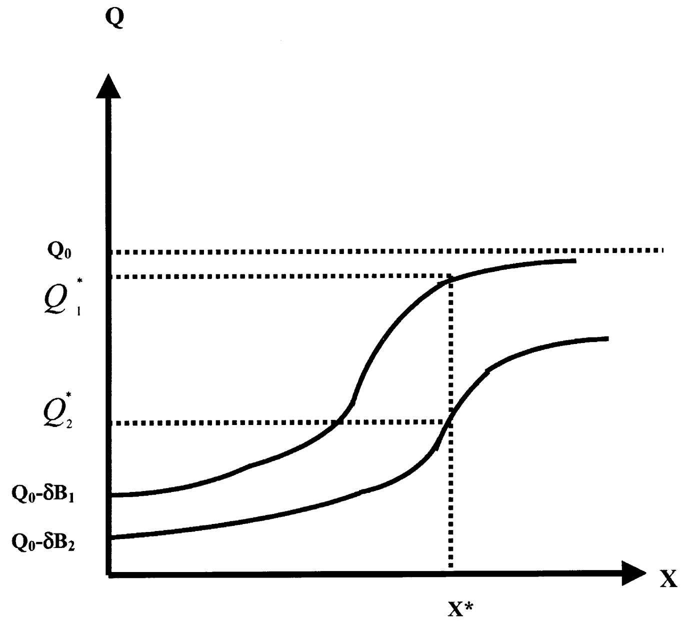


*Fig. 3.* Simplest Model with Linear Damage and $B_2 > B_1$.

Norgaard, 1973), the error term is correlated with the pesticide input X and the estimators are biased. Only when the pesticides are applied prophylactically, such as in a calendar-spraying program, would the bias be absent.

The solution to the problem of bias is to explicitly model the process generating the data, which must include the bug population. Rather than strictly continue with the damage control specification, we reformulate the problem. To do so, consider the motivation behind the approach. Output equals output without damage minus the damage. The damage equals output times the percentage change in damage, which depends on the infestation that survives the pesticide application, as shown in the Eq. (6) below. Equation (7) states that the percentage of the pest population killed depends on the amount of pesticide. Equation (8) constrains between zero and one both the percentage of damage and the percentage of the pest population killed by the pesticide.

$$Q = f(Z) - f(Z)H(B_A) \tag{6}$$

$$(B_B - B_A)/B_B = K(X) \tag{7}$$

$$0 \leq K(X),\ H(B_A) \leq 1 \tag{8}$$

To see how (5) relates to (6)–(8), solve (7) for $B_A$,

$$B_A = B_B[1 - K(X)] \tag{7a}$$

and substitute (7a) into (6) to obtain

$$Q = f(Z) - f(Z)H(B_B[1 - K(X)]) \tag{6a}$$

Since $0 \leq H(\cdot) \leq 1$, we see that f(Z) in (6a) equals $F_1(\cdot) + F_2(\cdot)$ in (5), the maximum possible output possible. From (6a), the maximum output possible occurs if either: (a) the initial infestation, $B_B$, is zero; or (b) the percentage killed is 100%, $K(X) = 1$, so that $H(0) = 0$. From (5), the maximum output occurs if $G(\cdot) = 1$, i.e. damage is zero. To model the process that generates the data, we have, therefore, substantially revised the damage control model.

To continue with this reformulation, let $B_B$ and $B_A$ be the initial infestation of the bug population (before application) and the surviving bug population (after application of pesticide). The most tractable function is the exponential. Specify the percentage of crop damaged and the percentage of the pest population killed as follows:

$$H(B_A) = [1 - \exp(-\delta B_A)] \tag{9}$$

$$K(X) = [1 - \exp(-\kappa X)] \tag{10}$$

Substituting these functional forms into the general expressions above, and adding multiplicative error terms results in the structural equations:

$$Q = f(Z)\exp(-\delta B_A + \varepsilon) \tag{11}$$

$$B_A = B_B \exp(-\kappa X + \eta) \tag{12}$$

In Eq. (11) above, as the surviving bug population after application goes to zero, output approaches f(Z), and as the surviving bug population approaches infinity, output goes to zero. Similarly for the kill function, as $X \rightarrow 0$, $B_A \rightarrow B_B$, and as $X \rightarrow \infty$, $B_A \rightarrow 0$.

Why reformulate the problem? First, the system of equations is linear after taking logs, so the estimation procedure is standard. Second, it is easy to further modify the model to account for phytotoxicity and retain a log-linear model, as shown below. Third, the original damage control specification was formulated for easy comparison to the Cobb-Douglas so the bias of historical studies could be easily recognized. That purpose was well served, but to make that comparison, Lichtenberg and Zilberman set $F_1(Z)$ to zero. From the original damage control formulation of the problem, $F_1(Z)$ has no interpretation except as the minimum output, whereas Fig. 3 shows that $F_1(Z)$ equals output ($Q_0$) if no infestation occurs minus the damage (δB) done by the infestation if left uncontrolled. Setting $F_1(Z)$ to zero implies that the initial infestation must be a very special population level – that level which would exactly destroy the entire crop and no more nor no less. By reformulating the problem we avoid the temptation to make such a peculiar assumption.

Fourth, in the original damage control specification, the interior solution guarantees that the marginal product of pesticides is always in Stage 2 of production, an undesirable assumption. It is desirable that the specification permit both Stage 1 and Stage 3, as well as Stage 2 of production. Different levels of initial pest infestation correspond to shifts in the marginal product curve for pesticides. Ceteris paribus, the model should allow for the possibility that at low levels of pesticide application, the marginal product curve rises with increasing amounts of pesticide. The shape of the marginal product curve at low doses relative to higher ones reflects the efficacy of the pesticide relative to the rate of damage caused by the remaining pest population. Phytotoxicity could cause the third stage of production to occur. Now let us check whether the extended damage control specification in Eqs (11) and (12) has these desirable properties.

Dropping the error terms for now, the reduced form is given by:

$$Q = f(Z)\exp[-\delta B_B \exp(-\kappa X)] \tag{13}$$

The marginal product of pesticides is given by:

$$MP_X = B_B f(Z)\delta\kappa \exp[-\kappa X - \delta B_B \exp(-\kappa X)] \tag{14}$$

Since the exponential function is everywhere positive, and so are $B_B$, $\delta$, and $\kappa$, the marginal product curve is positive, which rules out Stage 3.

Before we further extend the model to allow for stage 3, we further consider the properties of the marginal product. The intercept of the marginal product occurs where $X = 0$ and $MP_X = B_B f(Z)\ \delta\kappa \exp(-\delta B_B)$. The slope of the marginal product is given by:

$$\partial(MP_X)/\partial X = [-\kappa + \delta B_B \kappa \exp(-\kappa X)]MP_X \tag{15}$$

and this is greater than or less than zero depending on whether the term in [brackets] on the rhs is greater than or less than zero. As X approaches infinity, the term in brackets approaches $-\kappa$, so for sufficiently large X, the $MP_X$ is negatively sloped, and therefore this function supports Stage 2 of production. At $X = 0$, the expression in [brackets] is positive as long as $\delta B_B > 1$, which is determined by the data. So Stage 1 exists if supported by the data. The marginal product reaches a maximum where the slope equals zero, at $X^* = \{\ln[\delta B_B]\}/\kappa$, and at that point, $MP_X = \kappa f(Z)\exp(-1)$. Given the possible shapes of the marginal product of pesticides, the first order conditions for profit maximization are not sufficient for a maximum. Moreover, depending on pesticide prices, the corner solution $X^* = 0$ may maximize profit, quite apart from the corner solutions caused by fixed application costs or maximum legal doses (Hall, 1988).

To add in the phytotoxic effect of herbicides by allowing for stage 3 of the production function, simply let the percentage of damage to the crop depend on both the level of pest infestation, $B_B$, as well as the dosage of pesticide, X. The damage control specification is then further extended to:

$$Q = f(Z) - f(Z)H(B_A, X) \quad (16)$$

$$(B_B - B_A)/B_B = K(X) \quad (17)$$

$$0 \leq K(X),\ H(B_A, X) \leq 1 \quad (18)$$

For the special case of the user friendly exponential, we have estimable structural equations:

$$Q = f(Z) \exp(-\delta B_A - \varphi X + \varepsilon) \quad (19)$$

$$B_A = B_B \exp(-\kappa X + \eta) \quad (20)$$

The coefficient $\varphi$ is the parameter that expresses phytotoxicity. For the moment, dropping the error terms gives the following reduced form:

$$Q = f(Z) \exp\{-\delta B_B[\exp(-\kappa X)] - \varphi X\} \quad (21)$$

Differentiating with respect to X gives the marginal product of pesticides,

$$MP_X = [\kappa\delta B_B \exp(-\kappa X) - \varphi]Q \quad (22)$$

This expression has the properties we want. The third stage of production occurs when the marginal product is negative, which occurs when

$$B_B\delta\kappa \exp(-\kappa X) < \varphi \quad (23)$$

Since the left-hand side of the inequality has the exponential function, which asymptotically approaches zero as the argument approaches minus infinity, for sufficiently large X the third stage of production occurs. In fact, setting the marginal product to zero, we can solve for the level of pesticide at which the third stage occurs:

$$X(\text{3rd Stage}) = [\ln(B_B\delta\kappa) - \ln(\varphi)]/\kappa \quad (24)$$

## 4. EMPIRICAL APPLICATION

The structural equations are written in log-linear form:

$$\ln Q = \ln[f(Z)] - \delta B_A - \varphi X + \varepsilon \quad (25)$$

$$\ln(B_A) = B_B - \kappa X + \eta \tag{26}$$

If f(Z) is the Cobb-Douglas, or a more general power function (de Janvry, 1972), then this is a system of equations which is linear in the parameters to be estimated. If data are available from farms, then standard procedures for system estimation are appropriate.

For the application at hand, the data are from a controlled experiment (Hall, 1988). The variables for which measures exist are the log of yield (ln Q), pesticide dose (X), the insect population after application ($B_B$) and the log of the insect population (ln $B_A$); there are no measures of the variables Z, nor is there a measure of $B_B$. With substitution of coefficients for the parameters, the model becomes:

$$\ln Q = \beta_0 + \beta_1 B_A + \beta_2 X + \varepsilon \tag{27}$$

$$\ln B_A = \beta_3 + \beta_4 X + \eta \tag{28}$$

where $\beta_2$ is zero if there is no phytotoxic effect of the pesticide, and $\beta_3$ is an estimator for the initial infestation.

A random plot design generated the data, with varying amounts of pesticide application determined by experimental design (Hall, 1988). Consequently, for this application, two stage least squares is appropriate. Single equation estimation is acceptable for Eq. (28). Ordinary least squares gives estimates for $\beta_3$ and $\beta_4$ which in turn generate predicted values for ln $B_A$ and $B_A$. Equation (27) is then estimated using the predicted values of $B_A$ as an instrument for $B_A$.

Tables 2 and 3 show the results of the estimation. For Eq. (27), called the damage equation in Table 2, none of the coefficients are significant. Since the pesticide is an insecticide, not a herbicide, it is reasonable to drop the phytotoxicity term from the first equation by setting $\beta_2$ equal to zero, and re-

***Table 2.*** Damage Equation (27) with Stage 3 (Phytotoxicity).

| Variable | Coefficient | Std. error | T-Stat | 2-Tail Sig. |
|---|---|---|---|---|
| $\beta_0$ | –0.7810256 | 5.8260843 | –0.1340567 | 0.8939 |
| $\beta_1$ | 0.0097632 | 0.0377757 | 0.2584514 | 0.7971 |
| $\beta_2$ | 0.6444547 | 2.1863014 | 0.2947694 | 0.7694 |
| Mean of ln Q | 0.778575 | | F-statistic | 0.220722 |
| S.D. of ln Q | 0.109926 | N = 52 | Prob(F-statistic) | 0.802733 |
| S.E. of regression | 0.522563 | | $\Sigma e^2$ | 13.38053 |

***Table 3.*** Pesticide Efficacy Equation (28).

| Variable | Coefficient | Std. error | T-Stat | 2-Tail Sig. |
|---|---|---|---|---|
| $\beta_3$ | 5.1002750 | 0.1008020 | 50.596946 | 0.0000 |
| $\beta_4$ | –0.7573642 | 0.1158406 | –6.5379877 | 0.0000 |
| Mean of ln Q | 4.590511 | | F-statistic | 42.74528 |
| S.D. of ln Q | 0.621281 | N = 52 | Prob(F-statistic) | 0.000000 |
| S.E. of regression | 0.460709 | | $\Sigma e^2$ | 10.61265 |

***Table 4.*** Damage Equation (27) Without Stage 3 (Without Phytotoxicity: $\beta_2 = 0$).

| Variable | Coefficient | Std. error | T-Stat | 2-Tail Sig. |
|---|---|---|---|---|
| $\beta_0$ | 0.9565107 | 0.0603293 | 15.854826 | 0.0000 |
| $\beta_1$ | –0.0015431 | 0.0005056 | –3.0520837 | 0.0036 |
| Mean of ln Q | 0.778575 | | F-statistic | 9.315215 |
| S.D. of ln Q | 0.109926 | N = 52 | Prob(F-statistic) | 0.003634 |
| S.E. of regression | 0.111893 | | $\Sigma e^2$ | 0.625997 |

estimate Eq. (27). When the phytotoxicity term is dropped and the damage equation is re-estimated, the results shown in Table 4 are significant for the damage equation; in this case the empirical results rule out Stage 3 of production.

## IV. CONCLUDING REMARKS

A rigorous econometric rationale for choosing the damage control model over other empirical models for pesticide studies is not evident. Even so, it may be intuitively appealing to use the damage control model and, if it is used, an extension which permits additional flexibility seems warranted.

The extended damage control specification for pesticide productivity, as developed above, allows the data to determine whether there exists Stages 1 and 3 of production exist, rather than assuming those stages of production do not exist. The corner solution of zero application is possible in the extended damage control specification so that organic farming (Hall et al., 1989) can be explained within the context of the model.

It is noteworthy that special studies may be needed for pesticide productivity estimates since, for example, United States Department of Agriculture and perhaps other official surveys of growers typically don't collect pest infestation information (except for subjective ratings by the respondents in some cases). Hence, controlled experiments or other special studies where scientists or independent pest control advisers measure pest infestations may be necessary.

## ACKNOWLEDGMENT

We thank Craig Osteen and Alfons Weersink for comments and suggestions.

## REFERENCES

Blackwell, M., & Pagoulatos, A. (1992). The econometrics of damage control: comment. *American Journal of Agricultural Economics*, *74*(4), 1040–1044.

Carrasco-Tauber, C., & Moffitt, L. J. (1992). Damage control econometrics: functional specification and pesticide productivity. *American Journal of Agricultural Economics*, *74*, 158–162.

Du, F., Morzuch, B. J., Moffitt, L. J., & Bhowmik, P. C. (2000). Statistical analysis of pest tolerant response with application to corn weed control. *American Journal of Alternative Agriculture*, *15*(3), 137–141.

Fox, G., & Weersink, A. (1995). Damage control and increasing returns. *American Journal of Agricultural Economics*, *77*(1), 33–39.

Hall, D. C. (1988). The regional economic threshold for integrated pest management. *Natural Resource Modeling*, *2*(4), 631–652.

Hall, D. C., Baker, B. P., Franco, J., & Jolly, D. A. (1989). Organic food and sustainable agriculture. *Contemporary Policy Issues*, *7*(4), 47–72.

Hall, D. C., & Duncan, G. M. (1984). Econometric evaluation of new technology with an application to integrated pest management. *American Journal of Agricultural Economics*, *66*(5), 624–633.

Hall, D. C., & Norgaard, R. B. (1973). On the timing and application of pesticides. *American Journal of Agricultural Economics*, *55*(2), 198–201.

Headley, J. C. (1971). Defining the economic threshold. In: *Pest Control Strategies for the Future* (pp. 100–108). Washington D.C.: National Academy of Sciences.

Headley, J. C. (1968). Estimating the productivity of agricultural pesticides. *American Journal of Agricultural Economics*, *50*, 13–23.

de Janvry, A. (1972). The class of generalized power production functions. *American Journal of Agricultural Economics*, *54*(2), 234–237.

Lichtenberg, E., & Zilberman, D. (1986). The econometrics of damage control: why specification matters. *American Journal of Agricultural Economics*, *68*(2), 261–273.

Marsh, T. L., Huffaker, R. G., & Long, G. E. (2000). Optimal control of vector-virus-plant interactions: the case of potato leafroll virus net necrosis. *American Journal of Agricultural Economics*, *82*, 556–569.

Moffitt, L. J., & Farnsworth, R. L. (1981). Bioeconomic analysis of pesticide demand, *Agricultural Economics Research*, *33*(4), 12–18.

Pandey, S. (1989). The econometrics of damage control: comment. *American Journal of Agricultural Economics*, *71*(2), 443–444.

Saphores, J.-D. M. (2000). The economic threshold with a stochastic pest population: a real options approach. *American Journal of Agricultural Economics*, *82*, 541–555.

Sunding, D., & Zivin, J. (2000). Insect population dynamics, pesticide use, and farmworker health. *American Journal of Agricultural Economics*, *82*, 527–540.